NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

A Limited Analysis of some Nonacoustic Antisubmarine Warfare Systems

by

Daniel Gerald Daly

March 1994

Thesis Advisor:	**M.D. Kite**
Co-Advisor:	**R.N. Forrest**

Approved for public release; distribution is unlimited

REPORT DOCUMENTATION PAGE	**Form approved OMB No. 0704-188**

1. AGENCY USE ONLY (*Leave Blank*)	**2. REPORT DATE**	**3. REPORT TYPE AND DATES COVERED**
	March 1994	Master's Thesis

4. TITLE AND SUBTITLE

A Limited Analysis of some Nonacoustic Antisubmarine Warfare Systems

5. FUNDING NUMBERS

6. AUTHOR(S)

Daly, Daniel G.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense, the U.S. Government, the Canadian Department of National Defence, or the Canadian Government

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The problem of Anti-Submarine Warfare early in the next century is examined. Nonacoustic detection methods including magnetic anomaly detection, laser radar, and hydrodynamic detection are examined. A simple analysis of their relative effectiveness is made.

14. SUBJECT TERMS

Anti-Submarine Warfare, Submarine Detection, non-acoustics, MAD, Laser Detection of Submarines

15. NUMBER OF PAGES

55

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF THIS ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18

Approved for public release; distribution is unlimited.

A Limited Analysis of some Nonacoustic Antisubmarine Warfare Systems

by

Daniel Gerald Daly
Major, Canadian Air Force
B.Sc., Royal Roads Military College, Victoria, 1981

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN APPLIED SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
March 1994

Author: Daniel Gerald Daly
Daniel Gerald Daly

Approved by:
M.D. Kite, Thesis Advisor

R.N. Forrest, Thesis Co-Advisor

J.N. Eagle II, Chairman
Anti-Submarine Warfare Academic Group

ABSTRACT

The problem of Anti-Submarine Warfare early in the next century is examined. Nonacoustic detection methods including magnetic anomaly detection, laser radar, and hydrodynamic detection are examined. A simple analysis of their relative effectiveness is made.

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGMENTS

My thanks to Professors Kite and Forrest for agreeing to work on this topic with me. The insights I have developed during this thesis research have proved very enlightening.

I am indebted to the many fine faculty members who taught me during my time in the United States. I would also like to thank my classmates of Antisubmarine Warfare section IX-23 for their support during a difficult time in my life, and for reminding me that there is life outside of school.

I. INTRODUCTION

A. BACKGROUND

It may seem difficult to justify any spending on Anti-Submarine Warfare (ASW), especially in a tight budgetary climate now the Cold War has been "won." Why use scarce resources on what may seem like fighting the last war again? Yet, although the threat of submarine forces to the re-supply of Europe is no longer credible, the threat of submarines to other activities has increased, and the world has become less predicable, and to some, more dangerous as a result.

Submarine building and export, far from fading in the post-Cold War era, is in fact a growth industry. The submarine by its covert nature remains a potent and desirable tool in the political arsenal. Benedict compares the military sales in the time frame 1982-85, and 1986-89 in constant 1989 dollars, and notes they decreased by 30–60 percent for most major weapon systems, except for submarine deliveries, which increased by 30 percent [Ref. 1]. Consider the following excerpt from the United States Naval Institute *Proceedings*:

> In 1992, export sales accounted for 32% of Russian military production. The industrial lobby is currently trying to push up the quotas so that they would be allowed to sell 40 to 50% of their production overseas [Ref. 2].

The vessels sold by the former Soviet Union for export were not always first-class. For Russian sales, this has changed:

> In the past, the Russians–concerned that their secrets would be compromised–were reluctant to export their most advanced weapons. They might fall into Western hands, or their combat use by export clients might provide Western intelligence with an understanding of their operation. In either case, their future effectiveness in Soviet hands would have been degraded by the development of Western countermeasures. With the end of the Cold War, this disincentive has disappeared [Ref. 2:p.39].

For example, *Red Star*, on 16 October 1992 carried an "advertisement" for a TANGO-class diesel boat [Ref. 3]. Thus, so-called Third-World powers[1] may be able to acquire state-of-the-art submarines.

Increased automation in the latest export submarines means that their small crews[2] need not be as well-trained in order to operate them. Also, the reductions in military forces world-wide have left a large number of professional submarine sailors, both nuclear and conventional, looking for employment. Consequently, it is not inconceivable that one or several submarines could be crewed by mercenaries. In addition, not all societies (or leaders of them) share the same reverence for life that Western societies do, and the idea of a submarine crew accepting martyrdom in a political statement, whether it be for sinking a Western combatant or a cruise ship, cannot be discounted.

The ASW threat is not going away, but may be growing as more capable platforms come into less "friendly," less stable hands. Concurrently, economic realities suggest that Canada's military budget will continue to decrease, leaving few resources to invest in new or technologically risky ASW systems. Why is ASW research of **immediate** concern? Not only are diesel–electric submarines poised to make an order of magnitude jump in capability, but it is generally accepted by ASW professionals that current systems developed for deep water ASW do not adequately address the present and future shallow-water problem. It is therefore critical to examine current ASW systems and ASW systems under development to see how best to counter this threat.

[1] Third-World: "Term that refers to the > 100 developing countries of Africa, Asia, Latin America, and Oceania. Typically...former colonies with traditional cultures, agrarian economies, high birthrates, and widespread poverty. Term...coined after World War II to characterize an emerging group of nations that did not align themselves politically with either of the two powerful groups of industrialized nations: The Capitalist World or the Communist Bloc." [Ref. 4]

[2] Example: The TR-1700 diesel–electric submarine has a crew of only 26. [Ref. 5]

B. OBJECTIVES

This thesis examines the problem of Anti-Submarine Warfare, particularly in shallow water. In the near term, defined as the next ten years, submarines in service and currently building will be the threat.

To address the near-term threat, some current nonacoustic ASW systems are examined for their applicability to shallow-water ASW, either as-is or with modifications. New submarine technology is examined for its effect on the ASW problem.

Finally, a summary is presented that will attempt to answer the following questions: In order to maintain an adequate level of capability, which nonacoustic ASW systems have minimal room for improvement and which systems should continue to be funded?

C. SCOPE

The research for this thesis was conducted at the unclassified level. The physics dealing with the ASW problem is, of course, not classified. Classification usually occurs when dealing with data gained from specific systems, for example, acoustic source levels from a submarine class, or vessel within the class. No such information was used in this thesis. All data concerning characteristics of performance, physical size, and equipment fit were gained from unclassified literature, primarily Jane's Fighting Ships. The conclusions drawn from the research are the author's, and do not necessarily represent those of the Canadian Air Force, the Canadian Department of National Defence, the United States Navy, or the United States Department of Defense.

D. ORGANIZATION

The first part of this thesis presents scenarios which are plausible for use of submarines against the Canadian Forces or their allies, provides a resumé of some of the current submarines, details implications of pending technological advances, and

discusses signatures which will be exploitable in the time-frame discussed above. The second part covers non-acoustic methods of submarine detection.

Appendix A examines the computing power that can be expected to be available in future ASW systems, and Appendix B is the listing of a MATLAB program used in Chapter Three.

II. THE THREAT

A. SUBMARINE TYPES

1. Nuclear Submarines

The navies of the United States, United Kingdom, the ex-USSR (Russia and Ukraine), France, People's Republic of China (PRC), and India operate nuclear powered submarines. The nuclear-powered submarines provide long submerged endurance, considerable speed, and, in general, more volume for weapons and stores than do conventionally powered submarines.

In current nuclear submarines, water is heated by passing it through the core of a reactor in a primary loop under high pressure, thus the appellation pressurized water reactor (PWR). In this process, contaminants in the water can become highly radioactive. Heat from the water is transferred to a lower-pressure secondary loop (which is not made radioactive because no mixing takes place), boiling the water. The resulting steam turns a turbine, which runs a generator, and, through reduction gearing, turns a propeller shaft. Some submarines may use generators to run electric motors which turn the shaft; this avoids noise from the gearing being produced. Some experimentation has been done with liquid-metal primary loops, but water remains the current system of choice. Nuclear submarines have essentially unlimited fuel endurance. A number of nations have been interested in possessing nuclear submarines, including Brazil, Canada, India, Spain, Pakistan, Turkey, and Argentina [Ref. 6]. The main problems with nuclear propulsion systems are that they are complex, requiring extensive engineering training and, additionally, they require considerable infrastructure ashore. A secondary problem, radioactivity, is becoming increasingly unpopular with many segments of society, as well

as being lethal to the crew (and environment) if handled improperly. Figure 1 illustrates a typical marine nuclear reactor (from Stefanick page 139).

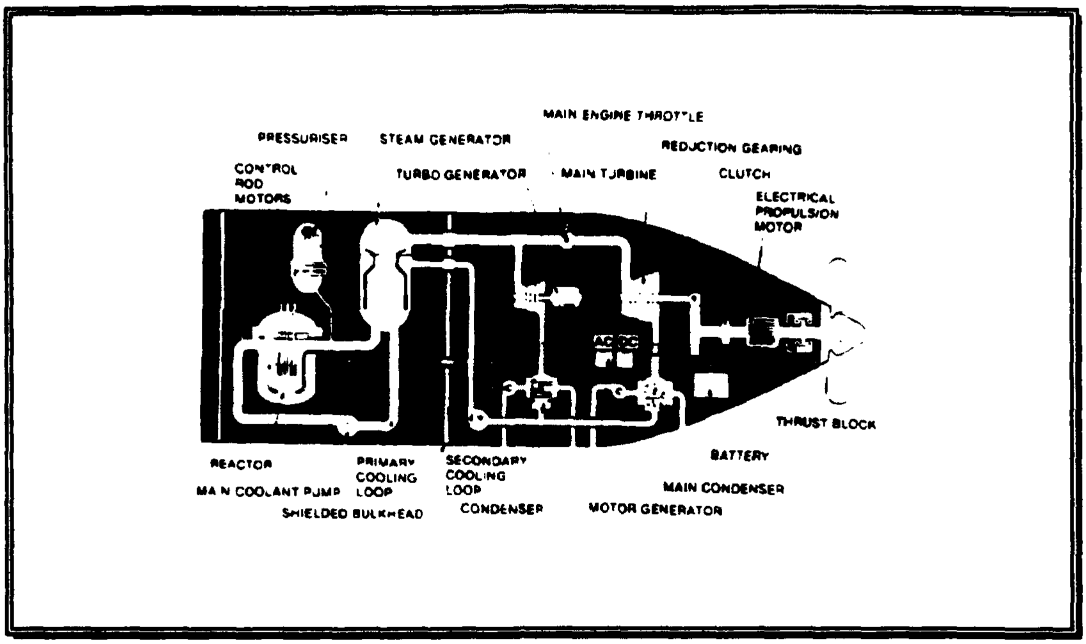

Figure 1 - Typical Pressurized water marine reactor

2. Conventionally Powered Submarines

Conventional submarines are operated by the nations mentioned in the introduction to nuclear power (save the United States, and very recently the United Kingdom), most of the NATO allies, and 20 Third World nations. Conventionally powered submarines are best suited for patrolling when great mobility is not required. A modern conventional submarine operating submerged on battery is very quiet acoustically, and virtually undetectable. As of 1 January, 1990, there were 408 operational submarines in 41 countries. Of these, about 200 belonged to Third World nations [Ref. 7]. Germany, the United Kingdom, France, Sweden , the Netherlands, possibly in the near future Australia, Russia, China, and North Korea export conventionally powered submarines [Ref. 8]. The following sections will briefly describe their operation.

Modern conventionally powered submarines are generally powered by diesel-electric propulsion systems. Diesel engines are used on the surface or with a snorkel to charge batteries which are used to power electric motors for propulsion underwater. While underwater, oxygen is stored in high pressure tanks, and released slowly to sustain the crew. Carbon monoxide, and other undesirable chemicals, are scrubbed from the air with chemicals if air cannot be exchanged via the snorkel. Such submarines are very quiet on battery operation, but they must operate on or near the surface frequently in order to recharge batteries and replenish their breathing air supply, rendering them vulnerable to detection by acoustic (engine sounds) and non-acoustic (visual, radar, etc.) means.

Modern diesel-electric submarines are very capable. An Argentine TR-1700 type submarine, *Santa Cruz*, was reported to have transited 6,900 nautical miles (NM) from the Bay of Biscay, 600 NM on the surface, the remainder submerged, to Mar del Plata in 29 days. The 6,300 mile submerged run was completed at an average speed of 10 knots snorkeling an average time of 2 hours a day. She arrived with a fuel reserve of 50 percent. [Ref. 9]

Figure 2 illustrates a typical diesel electric submarine (from Benedict "Third World Submarine Developments").

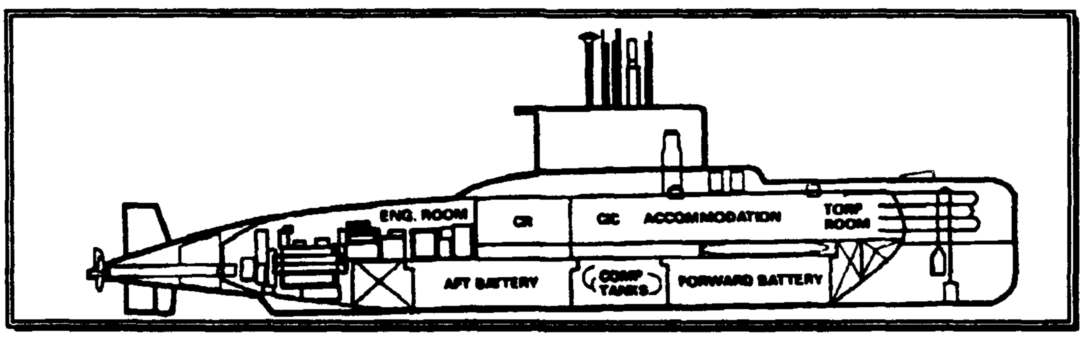

Figure 2 - German Type 209 Diesel Submarine

B. AIR INDEPENDENT PROPULSION DEVELOPMENTS

More recently, advances in several new technologies have drastically changed the anti-submarine conventionally powered picture, particularly Air Independent Propulsion (AIP) systems. AIP systems free the conventional submarine from surfacing to recharge batteries. The four major systems are Closed-cycle Diesel Engines, Fuel Cells, Stirling Engines, and Low-power Nuclear Reactors. [Ref. 10]

AIP is used in combination with diesel-electric technology, using AIP for patrol, and diesel-electric power when fast transit is required. Redundant systems also give increased safety for the submarine. Each of the AIP technologies is briefly described below:

1. Closed Cycle Diesel Engines

Recharging batteries with a diesel engine driving a generator has, in the past, required being on the surface, or with a snorkel mast near the surface. Even if a supply of air were available at depth, the requirement to discharge exhaust against great pressure has also robbed the engine of its usefulness. This has changed with the closed-cycle diesel engine, which recycles exhaust gas to the engine intake and adds oxygen to maintain a content of approximately 21 percent. The remaining 79 percent of inert gas is made up by adding argon gas, which provides the right volume and density for the compression heating and firing stroke of the diesel. Sea water is used to absorb exhaust products from the engine, and the exhaust-filled sea water is exchanged for clean sea water. The inter-relationships between argon, oxygen, and flow rate of exhaust-absorbing sea water are controlled by a microprocessor.

This new process uses only 10 to 15 percent of the engine's energy leaving sufficient energy to propel the ship and charge batteries. Closed-cycle diesel engines have also been proposed as emergency back-ups for nuclear submarines. Small prototype engines (25–kilowatt) have been operated since 1982, and larger units are planned (400-

600 kilowatt). [Ref. 11] Considerable interest in the process for the deep-water oil exploration industry virtually assures continued development.

This system is in use in an Italian midget submarine *Maritalia* (150–ton), with more than a week of submerged endurance, at depths of up to 300 meters. [Ref. 1:p.58] Figure 3 illustrates a typical closed–cycle diesel engine (from Fox page 29).

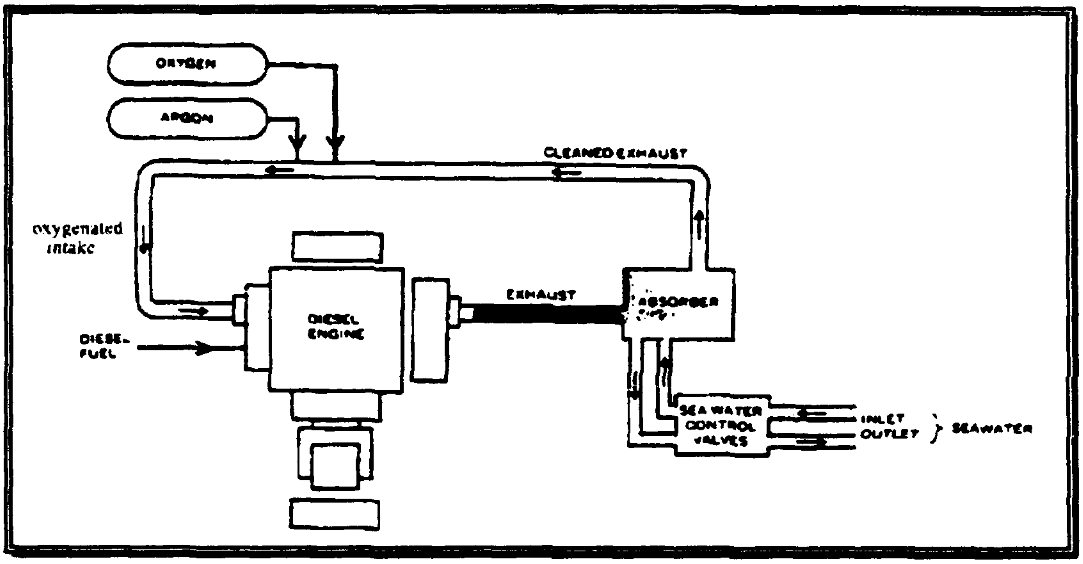

Figure 3 - Closed-cycle diesel engine

2. Fuel Cells

Oxygen and hydrogen are combined in a fuel cell in a continuous chemical reaction that directly produces electricity without any combustion. The German Navy has tested this system in a Type–205 submarine (450 ton), and published reports suggest 1 month submerged operations should be possible. The system is reportedly 50–70 percent efficient, and, significantly for ASW purposes, is very quiet due to a lack of moving parts and combustion [Ref. 1:p.58, Ref. 8]. Figure 4 is an abbreviated schematic diagram of a typical fuel cell system (from Benedict).

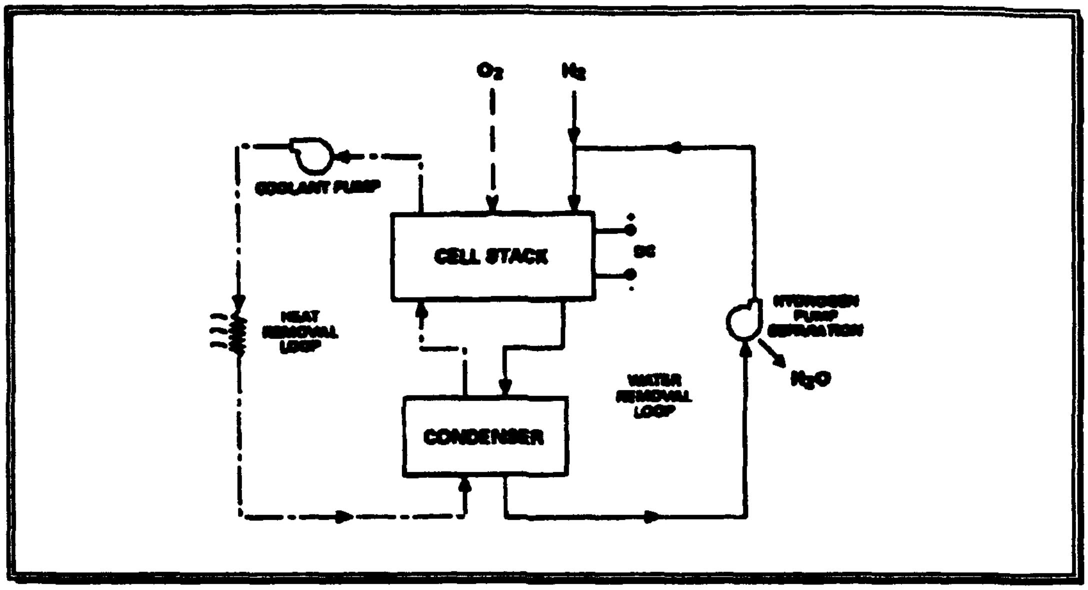

Figure 4 - Fuel cell

3. Stirling Engines

Stirling engines have been operated by the Swedish Navy in the A14–class submarine *Näcken* (1000 tons) since 1989 [Ref. 12]. The system produces heat from liquid oxygen in an external combustion chamber that is transferred under a constant and relatively low pressure to the engine via a heat pipe. The external chamber is kept in over pressure to facilitate overboard discharge of exhaust at depths of 300 meters. This indirect heating technology makes it possible to separate the engine from an external heating system, which limits risks [Ref. 13]. Reports of submerged endurance up to 2 weeks, and the ordering of a new class of submarine, the A19 *Gotland*–class (first-of-class laid down 20 November 1992), reportedly powered by Stirling engines, suggests successful trials [Ref. 6]. Figure 5 illustrates a typical Sterling engine (from Benedict).

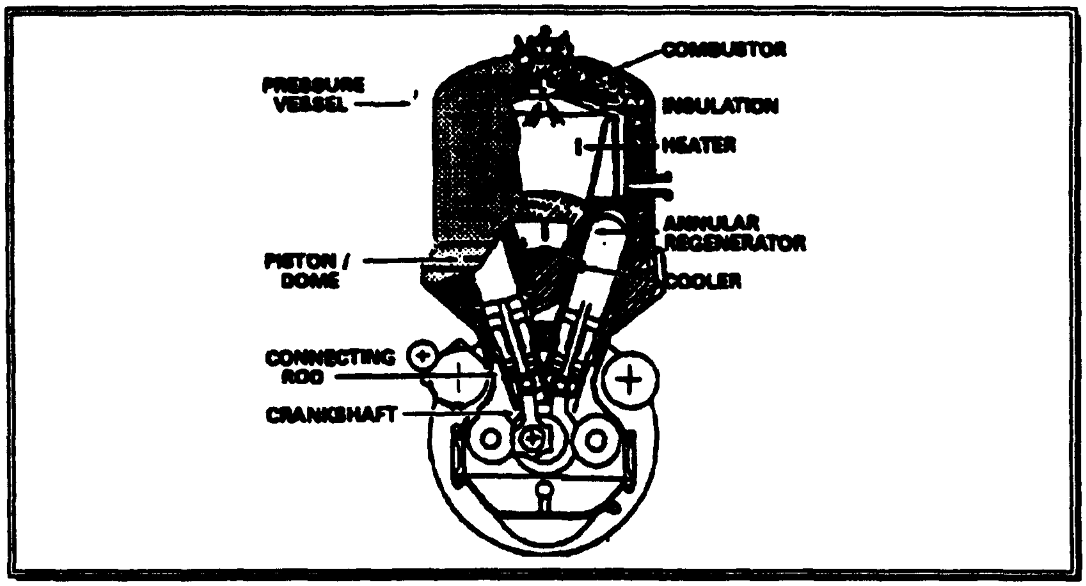

Figure 5 - Stirling Engine

4. Small Nuclear Reactors

In contrast to the large reactor providing high pressure steam, small nuclear reactors provide a "nuclear battery charger." [Ref. 13:p.53] A Canadian design, the autonomous marine power source (AMPS), has been licensed for unattended operation at research facilities ashore. It is scheduled to be installed on the French SAGA-1 commercial ocean submersible by 1995 [Ref. 6]. If these trials are successful, unlimited slow speed endurance would result. Sprint speeds would be limited, however. Figure 6 illustrates a typical low-power nuclear reactor (from Benedict).

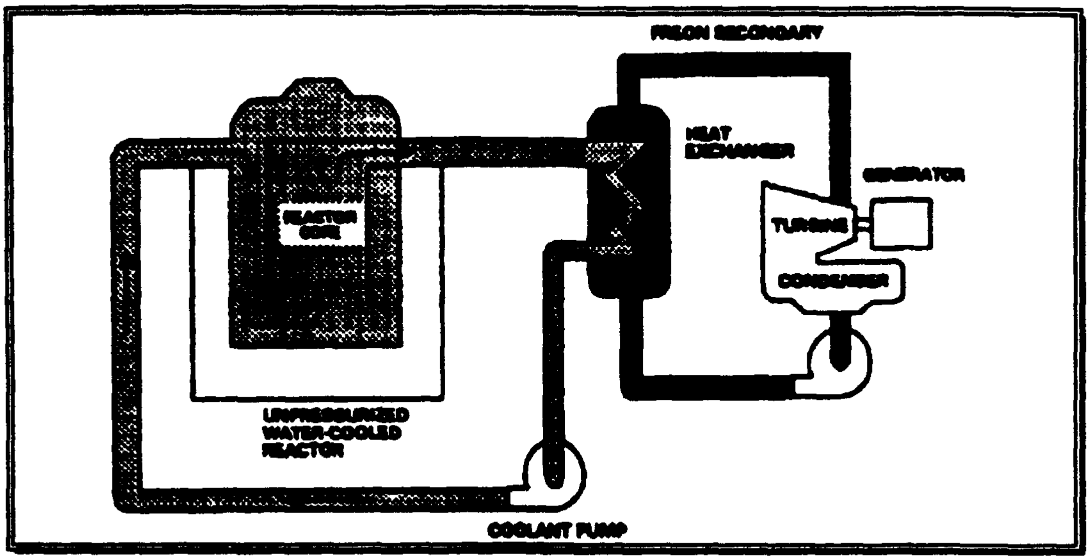

Figure 6 - 'Slowpoke' Nuclear reactor

Any of the above AIP systems will permit a conventional submarine to patrol with either extremely limited snorkeling, or none at all, during a patrol. A ratio of snorkeling time to patrol time is termed "indiscretion rate," as a submarine visible from the surface is considered to be indiscreet.

It is noted that a Russian non-nuclear submarine, the Beluga, was reported in the November 1991 edition of *Jane's Defence Weekly* to use an oxygen system (a fuel cell or Stirling-type engine). Similar in form to the Alfa-class SSN, it was completed in Leningrad in February 1987. [Ref. 1:p.57]

C. SUBMARINE "SIGNATURES"

A submarine's characteristic signatures that may be exploited by covert (passive) detection systems are shown in Figure 7. Exploited properly, the submarine may never discover it has been detected. In hostilities, it greatly enhances the ASW unit's likelihood of survival, as a hostile submarine's first indication of the presence of an enemy would be the noise of a torpedo in the water. Since a submarine is not aware that it is being observed by

a passive system, standard operating procedures and habits can be discerned, which aid the ASW force in detection tactics both in peace and war [Ref.14].

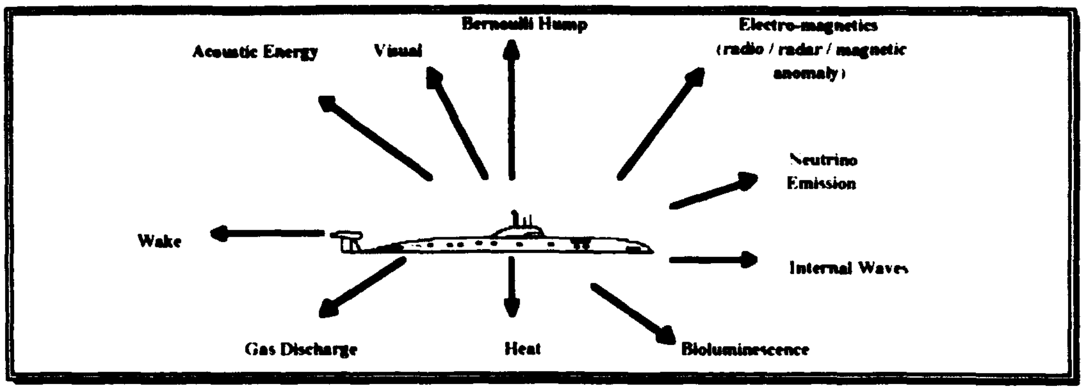

Figure 7 - Submarine Signature

In addition, ASW forces can overtly seek a submarine using active sensors, which may or may not result in counter detection. A resume of these sensor is contained in Figure 8 :

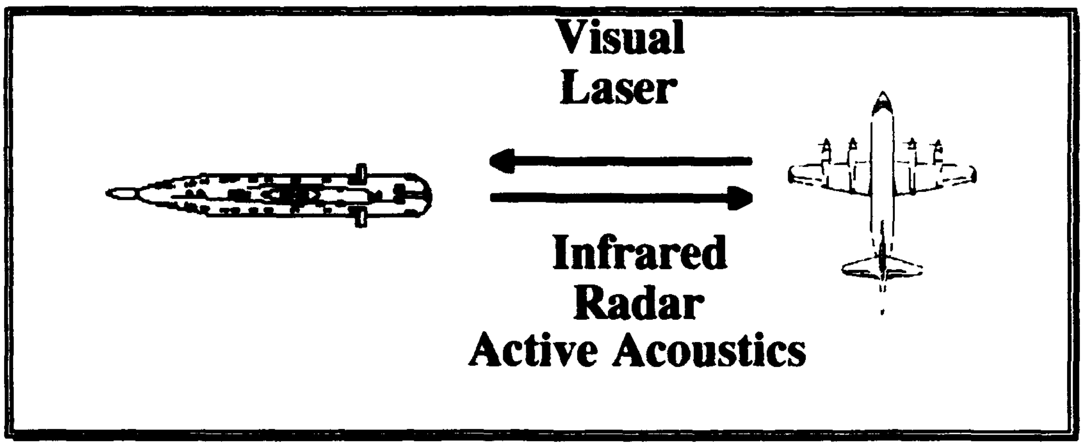

Figure 8 - Active Sensors

In addition to being classed as either passive or active, detection systems are classed as being acoustic or non-acoustic.

D. SCENARIOS

Where is the "threat?" Increasing numbers of more capable submarines in less friendly hands does not directly pose one. The future ASW threat depends on the scenarios under which hostile submarines might be utilized. It is not the intent of this thesis to examine all scenarios, but proposes the following four as possible for the Canadian Forces.

A "Peacemaking scenario" involves a peacemaking operation, against the will of a nation which possesses a small number of modern diesel-electric submarines. The nation is aligned politically with a larger nation which operates a number of nuclear powered attack submarines. Canada provides a naval force to enforce a blockade.

A "Home defense scenario" involves a nation which is denied access to fisheries within the 200 mile economic zone around Canada's coast, decides to force the issue, and sorties a surface force to protect their national interest. The nation also operates a modern submarine force, consisting of a small number of conventionally powered submarines, which were sighted leaving port, have not been located, and are presumed to be enroute to the Western Atlantic or Eastern Pacific.

A "Rogue submarine scenario" occurs when a nation possessing a large number of submarines reports that a number of submariners recently forced to retire have seized a submarine, left port, and are threatening to sink any vessel they encounter (or possibly, strike inland targets with submarine-launched cruise missiles) unless a ransom is paid.

A "Covert delivery scenario" occurs when a drug cartel, disturbed by high losses in other means of transporting drugs, buys modern submarines to off-load narcotics to North American shores.

In the near term, i.e., the next ten to fifteen years, two submarine threats will be used as examples of the range of targets ASW units could expect to encounter. Though they are current technology, they are very capable, and challenge current ASW systems.

1. Conventional Threat

The near term conventional submarine is a small diesel-electric submarine. The Thyssen Nordseewerke TR-1700 (built in Emden, West Germany) has been chosen as typical of current capability. This submarine has the following characteristics [Ref. 5]:

Displacement	2116/2264 tons (surfaced/dived)
Speed	15/15/25 knots (surfaced/snorkeling/dived)
Dimensions	66x7.3x6.5 meters (length/width/height)
Diving limit	270 meters
Weapons:	6 torpedo tubes
	mine capable
Range:	12,000 miles @ 8 knots surfaced
	20 miles @ 25 knots dived (battery)
	460 miles @ 6 knots dived (battery)
Crew:	26

The indiscretion rate of the TR-1700 on patrol is assumed to be half of that claimed on the voyage from Germany to Argentina cited above, one hour a day. This means, on average, eight percent of the time, the submarine will have to snorkel in order to charge batteries. During a rapid transit, the indiscretion rate would necessarily increase.

2. Nuclear Threat

The near term nuclear submarine is a relatively new SSN. Since it is unlikely that a threat would develop from a western power, or that a western power would export an SSN or SSN technology, a Russian Sierra II Class SSN has been selected (The second of five was in service in 1993). [Ref. 5]:

Displacement	7200/8200 tons (surfaced/dived)
Speed	18/32 knots (surfaced/dived)

Dimensions	111x14.2x8.8 meters (length/width/height)
Diving limit	650 meters
Weapons:	8 torpedo tubes (also missiles, tube launched)
	mine capable (50 or 60 in lieu of torpedoes)
Range:	unlimited
Crew:	100

The indiscretion rate of the SSN is near zero, as it need not ever leave patrol depth. Only tactical (final stages of attack) and National Command (communications) considerations would require the Sierra to be indiscreet.

Calculations for the effectiveness of nonacoustic sensors later in this thesis will be done using the characteristics of the TR-1700. It is assumed that larger submarines will have larger nonacoustic signatures due to their larger volume and mass.

III. SOME NON-ACOUSTIC DETECTION SYSTEMS

A. MAGNETIC ANOMALY DETECTION (MAD)

For distances greater than two submarine lengths, a submarine's magnetic field can be considered to be a magnetic dipole field superimposed on the earth's magnetic field. This field can be considered to be constant over the length of an encounter between a short-range sensor and a submarine. The magnetic field is made up of two major components: A permanent magnetic field and an induced magnetic field [Ref. 15]. The total field can be considered to be the vector sum of the permanent and induced fields.

For a fixed spatial orientation a dipole field decreases by a factor of $\frac{1}{r^3}$, where r is the distance from the sensor. The characteristics of a submarine's magnetic signal depend on:

- the size of the submarine.
- speed of the sensor relative to the submarine.
- the magnetic course of the sensor as it passes through the submarine's field.
- the magnetic course of the submarine.
- the effect of the natural magnetic background. [Ref. 9:p.606]

Magnetic fields are measured in Tesla (T) in the metric system. A Newton of force is caused by 1 Coulomb of charge moving at 1 meter per second in a one Tesla field. One Tesla equals 10,000 Gauss in the CGS system of measurement. One Gamma (commonly quoted for military magnetic anomaly detection sensitivities) equals one nanoTesla.

For some feeling for the size of the magnetic signature of the submarine, some relevant magnetic fields are given in Table 1 [Ref. 16]:

500 T	Pulsed electromagnetic fields (EMP).
100 T	strongest DC fields.
1 T	laboratory magnet.
1×10^{-2} T	refrigerator ceramic magnet.
$(30-60) \times 10^{-6}$ T	earth's field (equator-pole).
"few" 10^{-9} T	submarine magnetic signal.

Table 1 - Typical Magnetic fields

The ranges of current Magnetic Anomaly Detectors (MAD) are from 0.2 nanoTesla for the AN/ASQ-10A to 0.05 nanoTesla (nT) for the AN/ASQ-81 (MAD systems deployed on current U.S. ASW aircraft). This increase in sensitivity gives only a 59% increase in range, which is on the order of a few thousand feet [Ref. 17]. The AN/ASQ-208 digital MAD system has a sensitivity of 0.003 nT. It can be carried internally within an aircraft (other systems are towed or moved as far away as possible from any source of electrical or magnetic noise). The latest system is the Superconducting Quantum Interference Device (SQUID), which has been reported to have a sensitivity from 1×10^{-5} to 1×10^{-6} nT. At sensitivities this low, noise is a problem. [Ref. 16]

The main source of noise is geomagnetic, due to the interaction between the sun and the earth's magnetic field. The noise follows the sunspot cycle, with peaks every eleven years. Terrestrial effects of solar flares can be split into three types:

- Sudden Ionospheric Disturbances (SIDS) occur immediately (eight minutes) after a flare due to the arrival of x-rays. They affect the entire daylight portion of the earth and last as long as the flare.
- Polar Cap Absorption (PCA) starts fifteen minutes after the flare due to the arrival of protons from the flare. This lasts from one to ten days (normally around three). There are about seven to eight PCA events per year during the solar peak, and less otherwise.

- Ionospheric storms are caused by the arrival of the plasma clouds. Electron density increases and decreases in waves. The storms start twenty-four to forty-eight hours after the start of the flare, and last from two to five days [Ref. 18].

All three phenomena have the same effect on a MAD sensor. It is swamped with noise. Storms occur, on average, about fifteen percent of the time, and no accurate prediction system exists to forecast them. The effect of the storm increases with magnetic latitude due to convergence of the magnetic meridians. There are also daily variations in the earth's field due to solar heating that are latitude dependent. Figure 9 shows a typical MAD trace taken in a moderate magnetic storm [Ref. 17:p.187]:

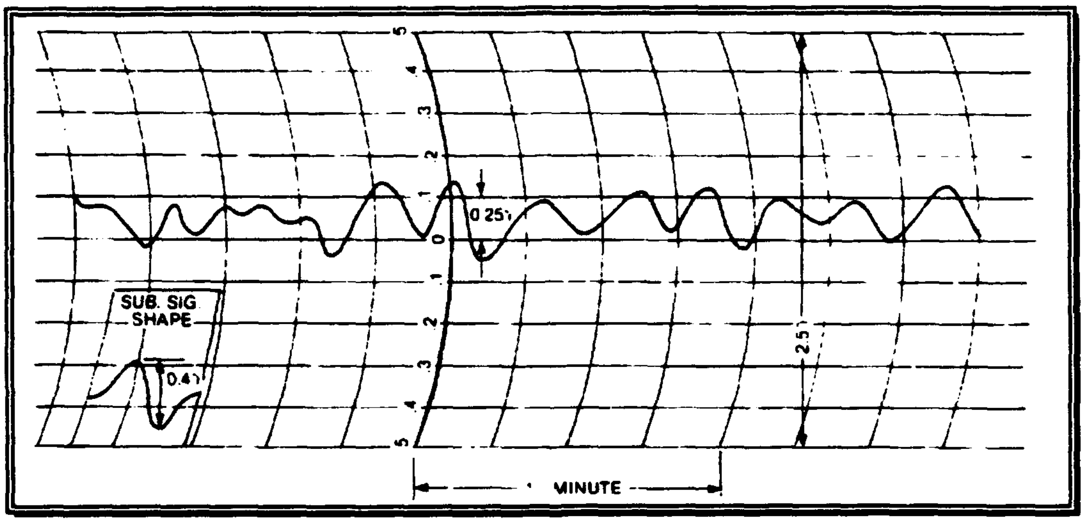

Figure 9 - Magnetic noise in an ASQ-10 MAD system due to a moderate magnetic storm, compared with a submarine-generated signal.

Geologic formations can cause great local disruptions to the magnetic field, causing false magnetometer readings. Maneuvers of the ASW platform (such as aircraft banking) cause the sensor itself to change orientation within the magnetic field, causing a false signal to appear on the sensor display, and use of certain transmitters on the aircraft, or in the local area, also cause false signals. Positioning the sensor close to the center of gravity of the aircraft minimizes this effect, as does the use of internal MAD rather than towed

systems. High powered radio systems also create a large magnetic field locally, causing man-made noise. This can be minimized by not transmitting during MAD prosecutions.

To summarize, any vessel made from magnetic materials has a MAD signature. It decreases as the cube root of distance, and does not propagate like a wave. There are significant natural and man-made noise sources. It is a good sensor for close-in detections.

There has been interest in the use of non-magnetic steels (German Type 205 and 206 submarines) and building non-steel submarines (The Russian Alfa is widely reported to have a titanium hull). Non-magnetic steel has not been popular in more recent submarines for unknown reasons. Titanium is half as dense as steel and non-magnetic, but has major disadvantages:

- cost ($33,000 per ton).
- inadequate resistance to brittle fracture (especially at low temps found in the deep ocean).
- special gas welding techniques are required.
- mainly foreign reserves. (US has only 3.5% of world reserves). [Ref. 17:p.137]

Recent Russian submarines have not been constructed with titanium hulls, presumably for reasons of cost.

1. MAD encounter simulation

An encounter between a MAD sensor and a submarine can be simulated using a computer program. One program computes estimates that a system such as the AN/ASQ-81 will detect a submarine dipole field during an encounter between an aircraft (moving with constant course, speed and altitude) and a submarine (moving with constant course, speed and depth). Using values for World War II submarine magnetic fields, and assuming they are valid for a modern diesel electric submarine, calculations were made to show the sweep width of the AN/ASQ-81 against a TR-1700 (2264 tons) in the waters off Sable Island, Nova Scotia (approximately 44°N 60°W, variation 22°W). A magnetic noise of 0.35 gamma, equivalent to moderate geomagnetic storm noise, was used. Figure 10 is a

trace of lateral range versus probability of detection at closest point of approach (CPA) in a straight line encounter [Ref. 15].

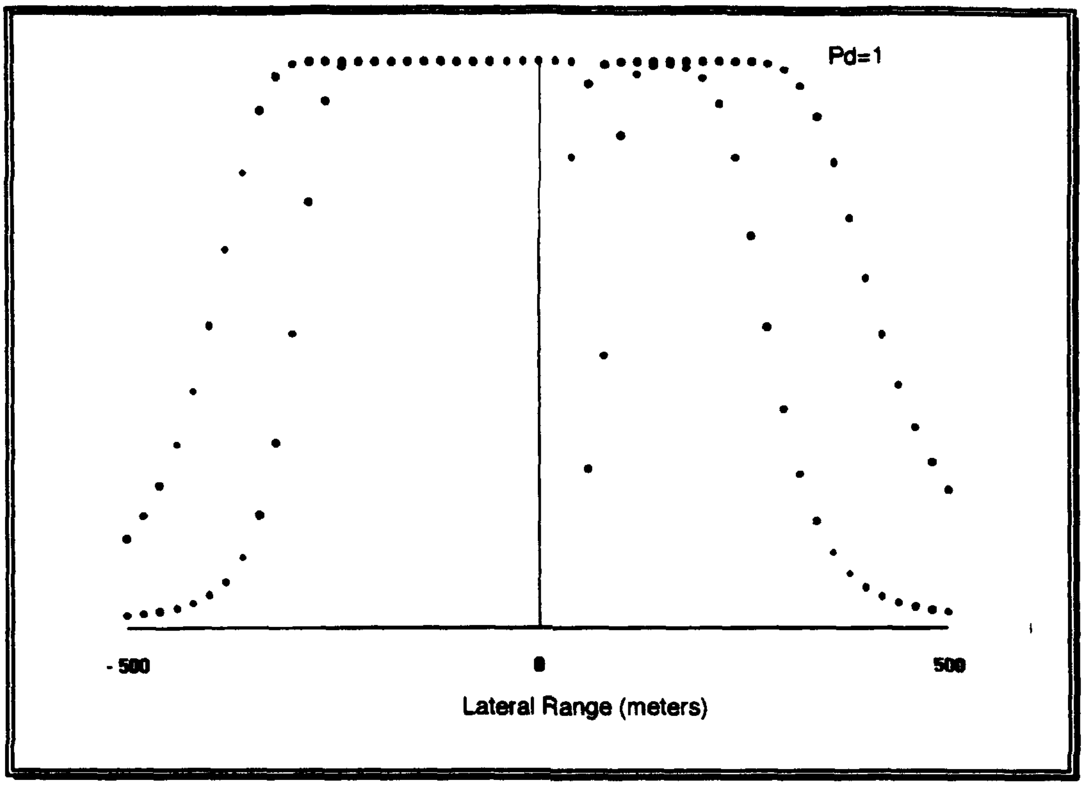

Figure 10 - Lateral Range versus probability of detection at CPA for a straight line encounter between a MAD sensor and a submarine

The upper curve is based on a crosscorrelation detector (the target signal is known) and it represents an upper bound for a detector's performance. The lower curve is based on an energy detector, which represents a lower bound for a detector's performance. The drop after zero lateral range and lack of symmetry in the lateral range curve is due to the nature of the dipole fields, and is target aspect dependent (here, MAD course 290°, submarine course 020°) [Ref. 15]. From the figure, it can be conjectured that the sweep width for an energy detection MAD is approximately 500 meters against a small diesel submarine. The lateral range curves approximate a "cookie-cutter" detection system, that is,

one that will always detect a target within the lateral range curve for a certain range and will always miss a target beyond that range. [Ref. 19]

2. Random Search Using MAD

Random search was selected because it is mathematically easy to calculate and understand, and because it provides a rough lower bound on search performance when a searcher attempts uniform coverage of an entire area but is thwarted by randomness in the target motion, navigation system errors and environmental uncertainties. The expected time required to first detect a target is:

$$E[T] = \frac{A}{Wv} \qquad (1)$$

where A is the area to be covered, W is the sweep width (twice the detection range for a "cookie cutter" detection system), and v is the speed of the searcher.

The probability of detection with a search time equal to or less than t time units is given by the function:

$$P_d(t) = 1 - e^{-\frac{Wvt}{A}} \qquad (2)$$

where $P_d(t)$ is the probability of detection by that time [Ref. 19:p.2-4 to 2-7].

As an example, suppose a submarine is in an area 40 nautical miles by 40 nautical miles. Assume an ASW unit searches the area with a speed of 240 knots and a detection system with a sweep width of 500 meters. Then, $E[T]$ would be 24.7 hours, and the probability of detection of the submarine 0.63 by that time. This example will be used as a basis for comparison to other sensors.

B. HYDRODYNAMICS

There are many types of hydrodynamic disturbance caused by submarines, for example, the Bernoulli Hump, Kelvin Wake and Vortex shedding.

1. Bernoulli Hump

The near-field surface wave associated with a submerged submarine, sometimes called a Bernoulli hump, can be considered the near-field of a source-sink pair ('the rankine ovoid'), which is geometrically a good approximation of a modern submarine hull [Ref. 17:p.193]. The shape of the Bernoulli hump is independent of speed and insensitive to depth. Water is displaced upward above the submarine, causing the surface of the ocean to rise. The water comes from an area behind the submarine, causing a depression in the ocean surface. Both these effects occur very close to the location of the submarine. The height, however, depends on both speed and depth. Table 2 gives some values for an *Ohio*-class submarine (from Stefanick page 195):

Depth (meters)	Speed (knots)	Height (centimeters)
30	5	1.1
30	12	6.5
30	20	19.0
100	5	0.10
100	12	0.59
100	20	1.60
300	5	0.01
300	12	0.07
300	20	0.18

Table 2 - Height of near-field wave (Bernoulli hump)

It can be seen from the table that a submarine can avoid producing a sizable hump by operating slowly or by increasing depth.

2. Kelvin Wake

The far-field solution for the surface waves are illustrated in Figure 11 [Ref. 17:p.196]:

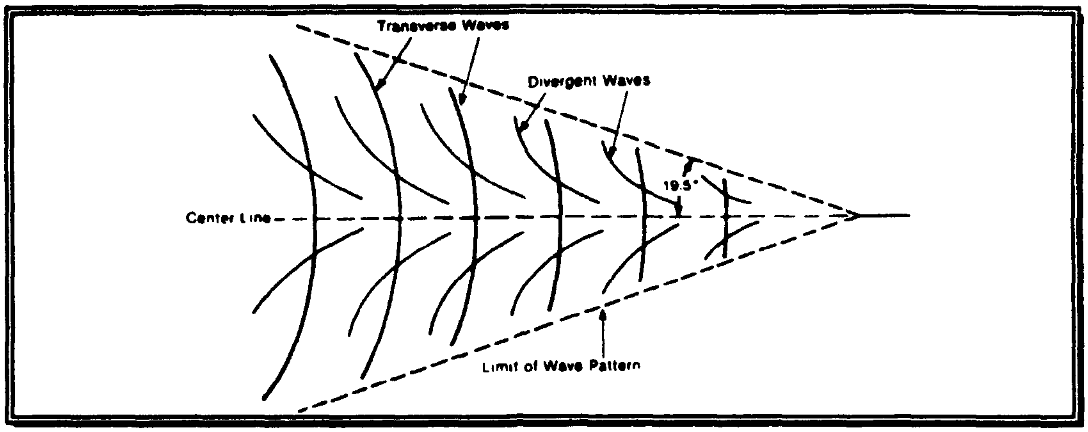

Figure 11 - Shape of far-field surface disturbance (Kelvin wake) over a moving submarine (Dimensions of the Ohio-class)

Two types of waves, transverse and divergent, may be present. Both will be contained within an angle of 19.5° of the direction of motion. Maximum wave heights for the far-field solution for various speeds and depths are given in Table 3 [Ref. 17:p.195].

		Centerline Wave Height (cm) @ Downstream Distance (m)		
Depth (m)	**Speed (kt)**	**100**	**500**	**10,000**
30	5	0	0	0
	12	0.13	0.1	0.02
	20	12.0	8.3	2.0
50	5	0	0	0
	12	0.001	0.001	0.0001
	20	1.9	1.3	0.32
100	5	0	0	0
	12	0	0	0
	20	0.02	0.01	0.003

Table 3 - Maximum far-field wave height due to a moving submarine

It should also be obvious that the smaller the submarine, the smaller the effect on the surface, but even a small submarine, say one accelerating away from the surface after an attack (torpedo or missile launch) may cause a considerable disturbance on the surface. In normal patrol, the wake would be much more difficult to detect. However in shallow water, submariners try to keep speeds low, as the size of depth excursions increase with speed, and in shallow water a submarine at high speed would risk either broaching (coming to the surface) or running into the bottom [Ref. 17:p.136].

3. Vortex Shedding

Submarines are generally operated with positive buoyancy. That is to say, in the absence of any other force, they will rise towards the surface. In practice this force is balanced with lift from control surfaces such as the diving planes. These are similar to airfoils, except they work to keep the vehicle down, not up. An area of high pressure is on the top, low pressure on the bottom. Water tends to flow from high to low pressure, so a vortex is shed off the end of the hydrofoil. The vortex rises towards the surface. An equation for the velocity of the vortex v_θ is given as equation (3):

$$v_\theta = \frac{\Delta B}{2\pi\rho u d w} \tag{3}$$

where ΔB is the buoyant force, ρ is the density of the fluid, u is the speed of the submarine, w is the width of the control surface, and d is the depth of the submarine.

Assuming the positive buoyant force is $1\text{x}10^5$ Newtons (approximately 21 tons; while this seems large, it represents only one tenth of one percent of the displacement of an *Ohio*-class submarine), a control surface width of 10 meters, a depth of 50 meters, and submarine speed of 5 meters per second (10 knots), and a water density of 1000 kilograms per meter cubed, a vortex speed of 0.006 meters per second is calculated. This is very small compared to wind-driven currents at the surface.

The vertical speed of the vortex is given by equation (4):

$$v_\theta(\text{vertical}) = \frac{\Delta B}{\rho u 2\pi w^2} \tag{4}$$

For the same example as above, the vertical speed can be calculated as 0.03 meters per second. It would take 1.7×10^3 seconds to rise the 50 meters to the surface, and would be 8.3 kilometers behind the submarine when it did.

The end result of one of Kelvin's other theorems is that vortices never end. Thus, a starting vortex occurs, and stays in place until friction dissipates its energy. This can be seen when paddling a canoe. Should there be a sharp turn, or a rapid control movement, a starting vortex, known as a knuckle, will be formed, which may persist. This phenomena would likely only be exploitable by another submarine. [Ref. 16]

Whether or not hydrodynamic phenomena are exploitable is open to question. The sizes of any of the effects on a submarine which is operated with any care are very small with respect to wind-driven gravity waves. Should a submarine be used by inexperienced personnel be operated at high speed at a shallow depth, however, it would be easily detectable. The calmer the water surface in the area, the easier it would be.

With the upcoming revolution in computer processing power (Appendix A), it is possible that the effects of wind-driven waves could be recognized, and a sensor set to ignore them since wind velocities are readily available to the computer from a number of air data sources. The presence of a wake, with the characteristic shape of the Kelvin wake envelope (19.5°), could be searched for by a crosscorrelation detector to maximize the detection probability.

Modulation of the wind-driven surface waves may cause radar backscatter to measurably change. Whether a detector with an acceptable false alarm rate could be constructed is an open question, and one which may bear investigation. If the surface effects are discernible, this technique is suited to both deep-water (SSN) detection, and

shallow-water use, though tides and current effects would make shallow water detections more difficult. Waves grow as they enter shallow water, and this exacerbates the problem of seeing the smaller waves due to hydrodynamic effects.

The use of a space-based system as a search sensor is considered unlikely since the effects are very limited in extent, the use of a space-based radar would require considerable power and the problem of transferring the bearing and distance obtained by a vehicle moving so quickly into a ground-based coordinate system (latitude and longitude) should a detection occur are formidable. An airborne sensor would be more appropriate for this technique.

It is assumed for the purposes of this thesis that a sensor exists which can detect the wake of a submerged submarine.

4. Sweep Width Using Wake Detection

The wake detection model is based on the following assumptions:

- A target wake is a moving straight line segment in a horizontal plane.
- The wake is detected if and only if the horizontal range of a detection system's sensor from at least one point on the wake is equal to or less than a definite value.
- In a straight line encounter, the angle between the projection of the sensor's track on the plane of the wake and the wake is a random variable that is equally likely to have any value between 0° and 90°.

The encounter geometry is shown in Figure 12 [Ref. 15][3] . The angle between the wake and the sensor's projected track on the plane of the wake is α, and the horizontal distance between the midpoint of the wake is x. The encounter geometry is at the time the midpoint of the wake is at the closest point of approach (CPA):

[3] The definite range circle in the Reference has been replaced by a definite range band for clarity, and the angle between the wake and sensor track has been repositioned correctly after discussion with the Reference's author.

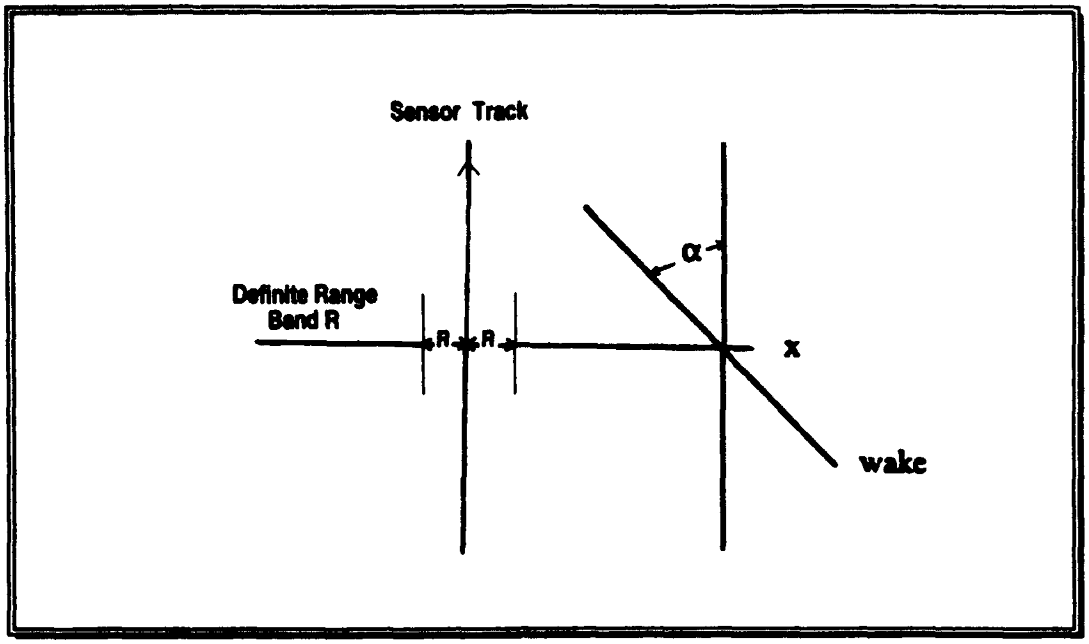

Figure 12 - Encounter geometry in the plane of the wake for a straight line encounter between a wake and a detection system's sensor

The sweep width of the sensor can be shown to be [Ref. 20]:

$$W = 2(R + \frac{\lambda}{\pi}) \tag{5}$$

where R is the detection range of the sensor.

λ is the length of the wake.

The formula shows that the sweep width is approximately twice the detection range of the sensor, with a factor to take into account the length of the wake. Since constant motion of the sensor would cut a rectangular swath, it is an appropriate model for a radar sweep.

A number of examples were done using the MATLAB computer language (Appendix B). A fixed detection range was assumed (100 and 1000 meters respectively). Two graphs of sweep width versus detection range are attached as Figures 13 and 14.

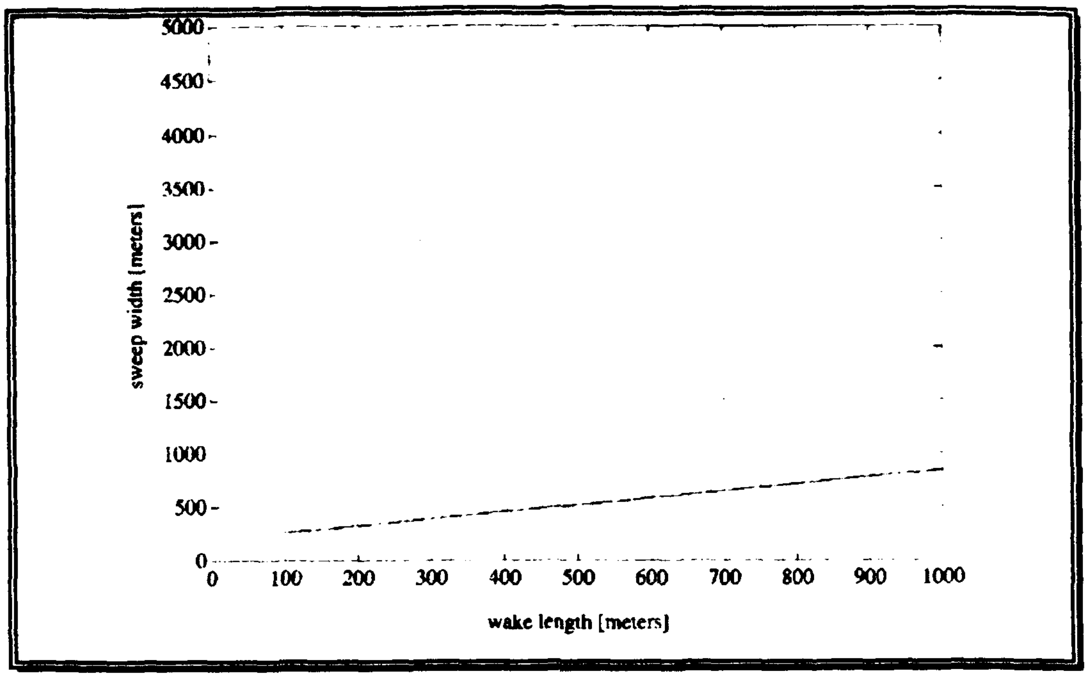

Figure 13 - Sweep width versus wake length with a fixed detection range of 100 meters

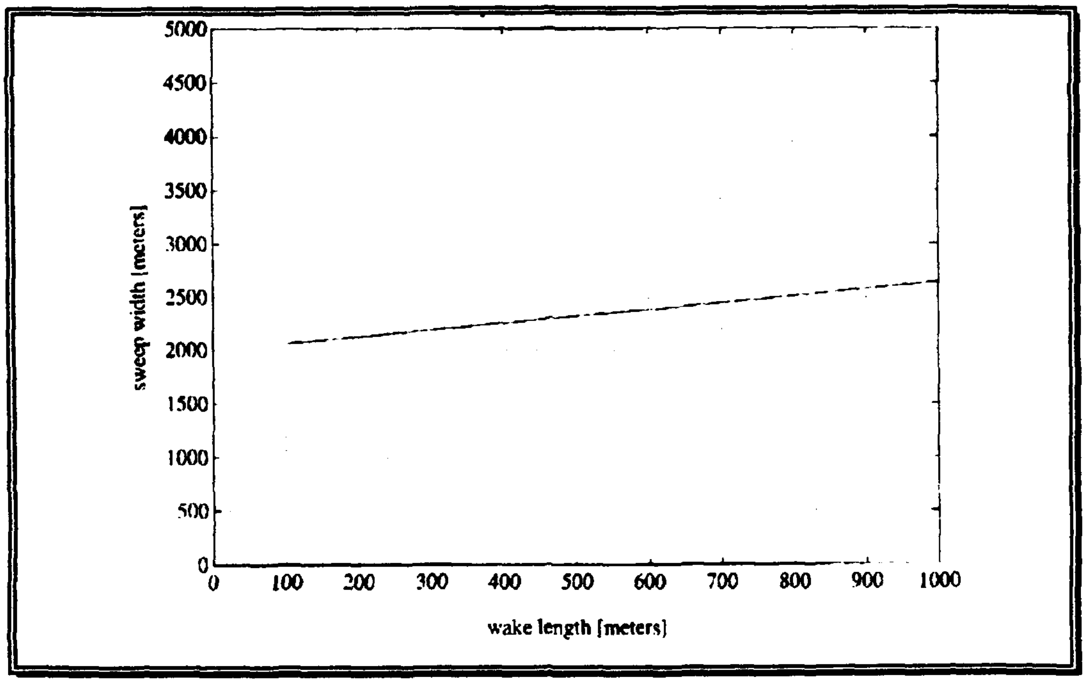

Figure 14 -Sweep width versus wake length with a fixed detection range of 1000 meters

The graphs show the most important factor of equation (5) is the detection range. An increase in wake length from 100 to 1000 meters with a fixed 100 meter detection range only increases the sweep width 600 meters, while a similar increase in detection range for a fixed wake of 100 meters increases sweep width 1800 meters. In other words, the formula for sweep width is relatively insensitive to wake length. The most gains can be realized by increasing the detection range of the sensor. The sweep width is approximately double the detection range.

5. Random Search Using Wake Detection

Assuming a detectable wake length of 100 meters, and a detection range of 1000 meters, the sweep width is 2063.7 meters. Using the same area as in the MAD example, the $E[T]$ would be 6.0 hours, with a detection probability of 0.63 by that time.

C. LASER DETECTION SYSTEM.

1. Overview of Laser Radar (Lidar)

The concept of laser detection of a submarine is very simple. A laser is pointed at the ocean, a pulse is sent, and a receiver plots the returned energy versus time. There are significant problems, however. The atmosphere and ocean attenuate the pulse through absorption and scattering, there are scattering losses from the submarine upon reflection, and returned energy must be discriminated from that reflected from the surface.

As early as 1967, a submerged submarine (USS Thread Fin) was detected as a target of opportunity during a mine-detection experiment near Panama City, Florida [Ref. 21] The laser used a 530.8 nanometer wavelength, 25 nanosecond pulse, a 5 inch (2 centimeter) aperture, and 2 megawatts peak power.

The wavelength of the laser is very important. Coastal waters are most transparent at a wavelength of light of approximately 500 to 550 nanometers, and the open ocean varies depending on which ocean is being measured, though it is usually around 470 nanometers.

[Ref. 22, 23]. Figure 15 shows the relationship between absorption coefficient (in m^{-1}) and wavelength in the ocean (in nanometers) [Ref. 16]:

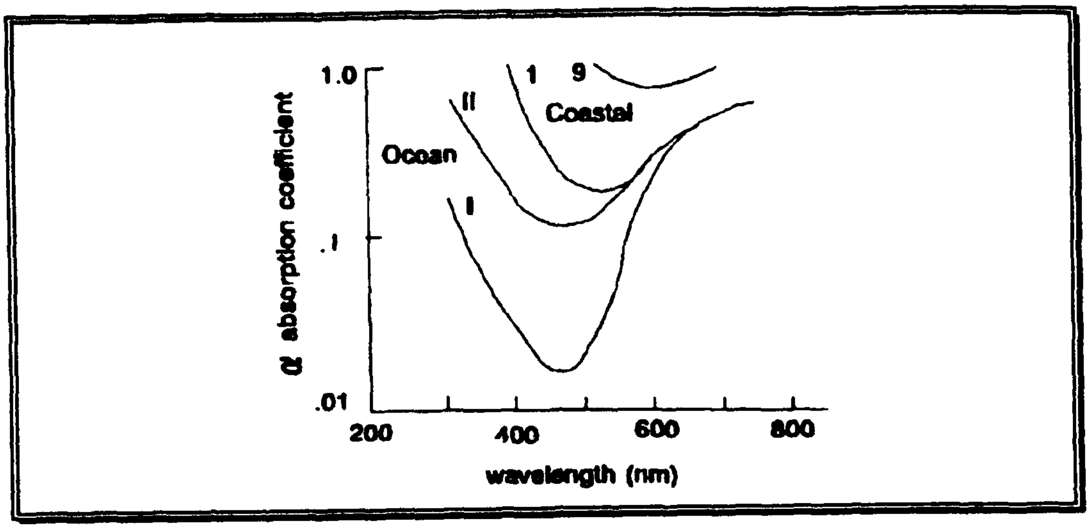

Figure 15 - Absorption coefficient (m^{-1}) versus wavelength (nanometers)

The major features of a laser radar (Lidar) trace are the transmitted pulse, the return from the surface, and the return from the target (if any). In deep water, the return will be attenuated to the point where the return is hidden in noise, and in shallow water, a return from the bottom is also displayed. Figure 16 shows a simplified diagram of a typical laser return in deep water versus time [Ref. 16]:

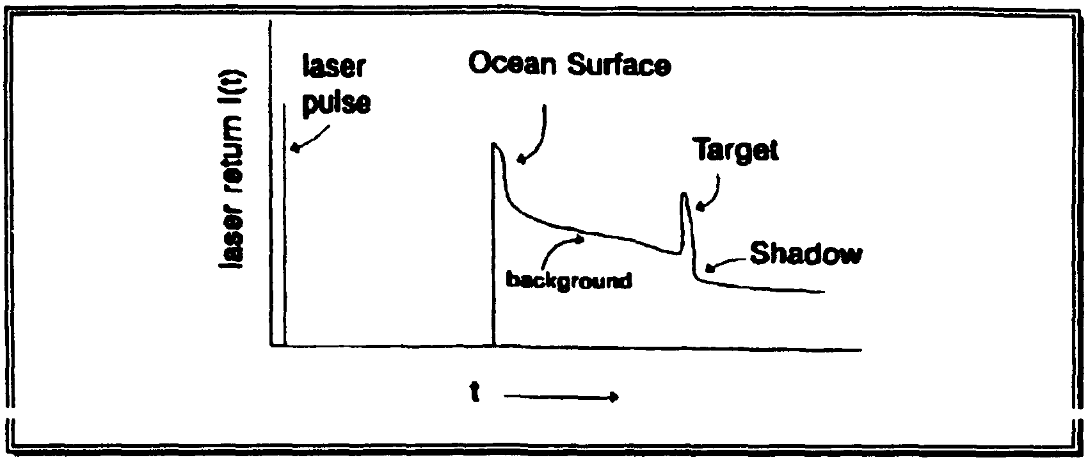

Figure 16 - laser return versus time

There are two separate cases which must be considered due to the geometry of the problem. The beam can be smaller than the submarine or larger. To explain which areas are being described in the formulae to follow, a diagram (Figure 17) is included [Ref. 16]:

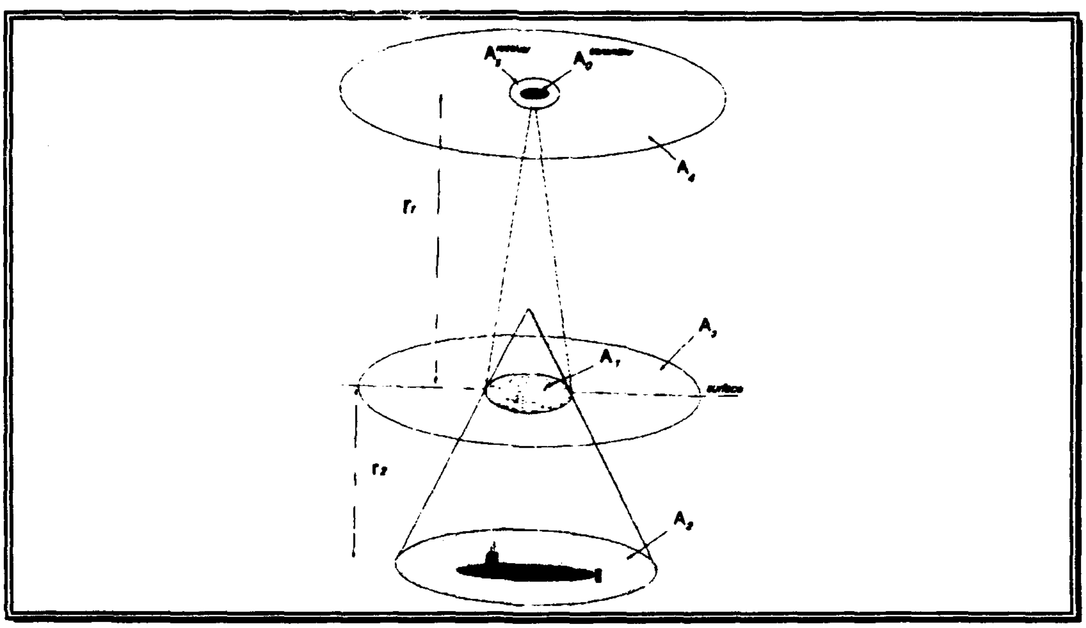

Figure 17 - Areas in Lidar formulae

If the beam is larger than the submarine (the case seen in Figure 17), the returned power to the aircraft receiver is given by equation (6):

$$P_r = \frac{P_t e^{-2\alpha r_2}(1-R_s)^2 \sigma_e A_5}{A_2 A_4} \tag{6}$$

where P_t is the transmitted power in watts, α is the absorption coefficient of water in meters^{-1}, r_2 is the depth of the submarine in meters, $(1-R_s)$ is the fraction of the intensity transmitted through a surface, σ_e is the cross sectional area of the target in meters^2, A_5 is the area of the receiver (aperture) in meters^2, A_2 is the area of the Lidar beam at the submarine depth in meters^2 and A_4 is the area of the returned beam at the aircraft altitude in meters^2.

If the beam is smaller than the submarine, the normal case, the equation (7) becomes:

$$P_r = \frac{P_t e^{-2\alpha r_2}(1-R_s)^2 R_t A_5}{A_4} \tag{7}$$

where R_t is the reflectivity of the target.

For diffuse reflection from a flat surface (Lambertian) the formula for the small beam becomes equation (8):

$$P_r = \frac{P_t e^{-2\alpha r_2}(1-R_s)^2 R_t A_5}{\pi A_4 (r_1+r_2)^2}\left(\frac{r_1+r_2}{r_1\frac{n_{water}}{n_{air}}+r_2}\right)^2 \tag{8}$$

where n is the index of refraction.

The back scatter from the ocean can be calculated by equation (9):

$$P_r = \frac{P_t e^{-2\alpha r_2}(1-R_s)^2 \beta(\theta) c\tau A_5}{2n(r_1+r_2)^2}\left(\frac{r_1+r_2}{r_1\frac{n_{water}}{n_{air}}+r_2}\right)^2 \tag{9}$$

where $\beta(\theta)$ is the dimensionless volume backscattering coefficient, c is the speed of light in meters per second, and τ is the laser pulse length in seconds.

Typically, in current systems, 100 to 1,000 photons are required for a detection. Energy is quantized, and this can be described by equation (10):

$$E = nhf \tag{10}$$

where n is the number of photons, h is Planck's constant, and f is the frequency in seconds^{-1}.

The energy of 100 photons in a 500 nanometer beam, of pulse length 1 nanosecond, is 4.0×10^{-17} Joules. Converted to power, this is 4.0×10^{-8} watts.

Graphically, a transmitted beam of 10 megawatts with no absorptive losses in the atmosphere, in very clear water (α of 0.02 meters^{-1}) would give the following results (Figure 18):

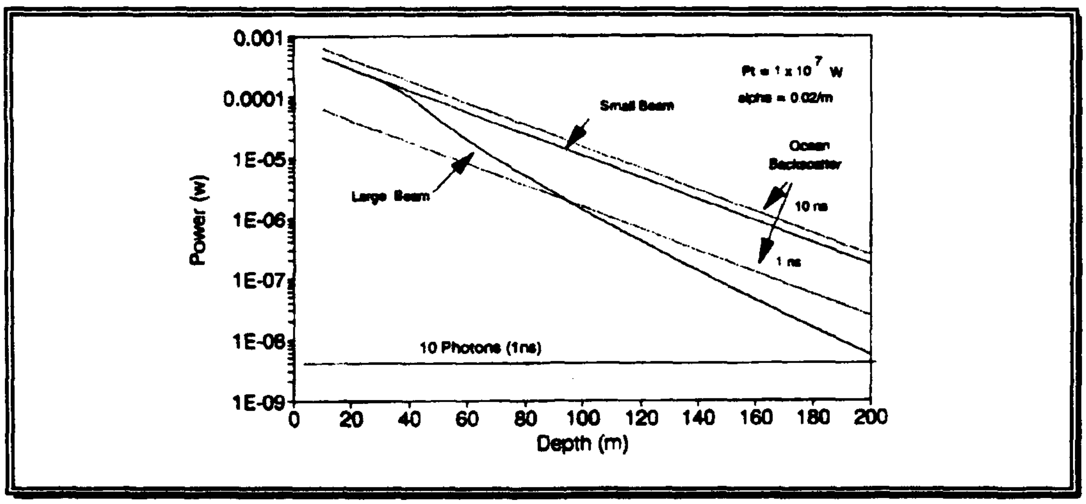

Figure 18 - Theoretical lidar return from a submarine, clear water

Several interesting things can be seen in the picture. First, the large beam acts like a small (non-spreading beam) for a small depth, then begins to spread (at about 40 meters). Second, the ocean back scatter for the longer pulse (10 ns) would totally obscure the returned signal. The small beam remains effective to depths of around 200 meters.

In more turbid water (α of 0.06 meters^{-1}), the light is less able to penetrate. Figure 19 shows the results of repeating the calculations with all else being constant (note the reduced depth scale):

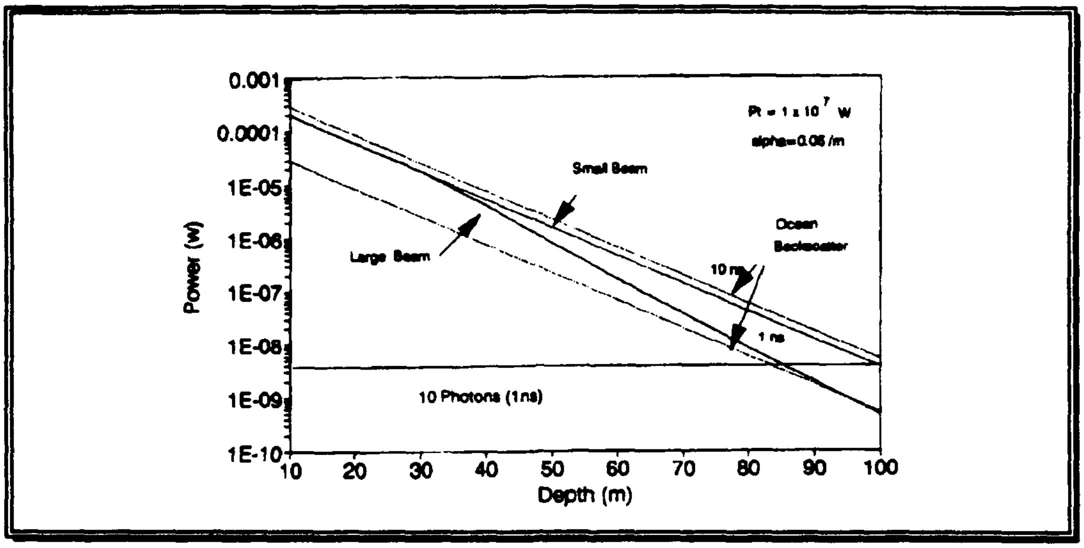

Figure 19 - Laser return from a submarine, turbid water

The reduced ranges (shallow water) can be offset by using a more powerful laser.

2. Random Search Using Lidar

The sweep width of the Russian Amethyst system, a blue-green laser carried by Bear-F Mod 4 aircraft, is reported to be 100 meters, with the aircraft at an altitude of 100 meters, and a speed of 200 knots [Ref. 24]. Assuming a system with these characteristics, and using the same area as in the MAD example, the $E[T]$ would be 123.5 hours, with a detection probability of 0.63 by that time.

D. ELECTROMAGNETIC SUPPORT MEASURES (ESM)

A submarine's use of radio or radar allows ASW units an opportunity to detect the submarine. A distinctive emitter signature can give away the identity of a submarine, which

makes the searching unit's job easier (knowing what to look for makes it easier to find). This is balanced by several factors in the submarine's favor.

First, the emitter probably operates in a band shared by a number of other radars, or radio transmitters. Having an emitter in the band may not indicate the presence of a submarine, just a fishing vessel. This problem will get worse as more navies adopt commercial-off-the-shelf (COTS) equipment, and identical systems are operated on combatants and non-combatants. Second, other electronic navigation and fire control systems have improved greatly, obviating the need to emit radar for navigation or final target solutions. Communication can be done almost undetectably by several means.

Submarine operations in shallow water used to mean that more emissions could be expected, because the submarine wished to fix its position more frequently, to avoid grounding. The use of the Global Positioning System satellite navigation systems has meant that a unit can fix its location covertly to a higher precision than hitherto was possible overtly with radar.

It is the author's experience that current electronic detection devices are limited by computing power. A balance has been necessary between coverage of all frequencies bands, and probability of detection of the most important signals due to the time-sharing of the processor. This compromise has meant that detection opportunities have been missed, according to post-exercise reports (personal experience). The advanced processing and storage capability of the upcoming computers (Appendix A) will give electronic warfare equipment the ability to monitor a larger range of the electro-magnetic spectrum simultaneously, resulting in higher probabilities of detection. Yet, this must be balanced by the fact the submarine may not have to transmit, due to the factors previously mentioned.

APPENDIX A - COMPUTING ADVANCES

One of the **major** drawbacks of current (and future) sensor employment is limited processing capability. In the past, specialized computers were developed specifically for ASW use. Because of the long lead times required to design and produce these computers, were obsolete on delivery. For example, many P-3 aircraft continue to fly today with 1970's vintage computers. The traditional computer research and development (R&D) leader, the military, has been replaced by industry. The advances commercial industry has made in processing, data storage and retrieval, reduced size, and increased reliability must be taken advantage of.

The thesis is based on the assumptions that ASW systems will increasingly rely on commercial-off-the-shelf (COTS) systems, also known as non-developmental items (NDI), and it is assumed that computers in military systems now in the final stages of development, and those on the drawing board, will almost certainly closely resemble those in the best contemporary technology. A recent article from *The Journal of Electronic Defense*, "Military Computing in the Year 2001 and Beyond" [Ref. 25] gives an excellent assessment of what Central Processing Unit (CPU) is likely to be found in a military computer in the year 2001.

Six microprocessors have been introduced in the 1992-93 time frame, all of which except one are super scalars, i.e., they are able to issue two or more instructions in a single clock cycle. Digital Equipment Corporation's Alpha 21604 (a reduced-instruction-set-computer (RISC) running at 200 MHz with 64-bit wide data registers), and Hewlett-Packard's PA7100 (100 MHz, 64-bit, RISC) chips were released in February 1992. The U.S. Air Force has announced that the Alpha chip would replace the Motorola 68040 processor in the E-8 Joint-STARS aircraft.

In May 1992, Sun Microsystems and Texas Instruments brought out the SuperSparc (60 MHz, 32-bit, RISC) which can issue three instructions per clock cycle. In November, MIPS Technologies Incorporated brought out the R4400SC (150 MHz, 64-bit, RISC). In 1993, Intel introduced the Pentium, which uses an older complex-instruction-set-computing (CISC) chip, and Motorola introduced the PowerPC 601 chip (80 MHz, 32-bit, RISC), able to issue three instructions in a clock cycle. Both IBM and Apple computer will produce home computers with performance heretofore only seen in (and sometimes surpassing) mainframe workstation computers.

The next generation chips will be even faster. Digital's Alpha 21064A (275 MHz, 64-bit, RISC) promises a 30 percent increase in integer (i.e., normal computing operations) and 60 percent increase in floating point (i.e., mathematical calculations) performance. But what does this mean?

As microprocessors speeds increase, the limit on what a single chip can do is being approached. The future is between the single chip, and the "massively parallel" megaprocessors used in supercomputers, in a niche known as "arrayed microprocessor." The newest Silicon Graphics family of processors (R-4400, RISC, 4 instructions per clock cycle, throughput of 300 MFLOPS (300 million floating point operations per second - equivalent to the current Cray Y-MP supercomputer)) use such technology, are expected to achieve between 2.7 and 5.4 GFLOPS (billion floating point operations per second). Compare this with a common system with today's technology, the Intel-80386 running at 20 MHz, which achieves 232 KFLOPS (that is, 0.000232 GFLOPS). Capability for mathematical operations will be 20,000 times what they are today.

Mass storage systems have kept pace with the increased power of the central processing units. Storage of data used to be done on magnetic tapes, which were slow to find any but sequential data, and required bulky readers. These were replaced with quickly rotating magnetic drum storage, which allowed much quicker access to any stored data.

These systems were capable of storing a few megabits of data in the early 1970's, and are still used in some airborne systems such as the CP-140 Aurora Maritime Patrol Aircraft.

In the 1980's, systems made up of stacked rotating platters of magnetic media, hard disks, became the commercial norm. Access speeds increased, and the ability to pack more data into the same area increased. By the end of the decade, systems able to store Gigabits of data were common. These systems can be linked in arrays to provide inexpensive, effectively limitless mass storage. In the 1990's, systems still use magnetic media, but the trend is toward the use of optical media. These use low power lasers to modify the surface c[illegible]se into orientations which the systems can recognize as binary data. They do not deg[illegible]de in the short term (ten years), are resistant to electro-magnetic pulse, and are very light. Access speeds are slightly slower than magnetic media, but this problem will be cured in the near term. Again, arrays of these disks represents unlimited storage, so that libraries of threat submarine data can be carried, and the greater processing power of the aircraft computer could be used for automatic detection.

Based on the above, the COTS military computer projected to enter service in the year 2001 is expected to run at clock speeds of 2 GHz or faster, and be capable of speeds equivalent to a Cray C90, that is, about 1-GFLOPS operation.

Current ASW systems are held back by computing considerations. For example, monochrome displays are common, because the computing power to display color is not available (for 256 color operation, every picture element requires an extra 8 bits of data). Operators' ability to recognize targets will improve, because more information will be displayed. Studies have shown that the average human can recognize five to twenty-five hues within a color (as might be seen on a "waterfall" acoustic display), but can recognize 256 colors [Ref. 26] As well, automatic detections, which are based on only a small amount of information and limited threat libraries (due to throughput problems), and have been characterized as taking more time than they save, can be greatly improved. Also, the

number of sensors which can simultaneously be processed will increase. For example, instead of processing sixteen sonobuoys on a monochrome display, a future processor will be able to handle fifty or more, and multi-color displays will be the norm. With the advent of smaller, cheaper, more robust electronics, some of the processing hitherto done on board the ASW unit may be done by the sonobuoy instead.

The cost of the new hardware can also be justified because the ability to support vintage technology is also very costly. Chips which were inexpensive ten years ago due to mass production must now be produced one at a time, at considerable expense and long delivery times, when they fail. Current technology chips can be ordered off-the-shelf cheaply.

But hardware is only half the solution. At least fifty percent of the cost of a new system is due to software costs. It is assumed that spending will continue in developing software to use with new computers, and that the old software will not just be modified to run on a newer system.

The amount of information that can be linked to and from ASW units, and assets ashore, will increase greatly, allowing the use of a smaller number of much more capable units. In an era when there are fewer units, increased computing power will be required to make them more capable.

APPENDIX B - WAKE DETECTION MATLAB PROGRAM

```
% Matlab 3.5 program for sweep widths with various wake lengths, detection
% ranges. Daly. 23 March. Thesis chapter 3, wake detection.
clear
clg
axis([0 1000 0 5000]);                  % fix graph axis x 0 to 1000, y 0 to 5000
% first fix detection range R at 100 meters, vary wake length;
R=100;                                  % det range in meters
lambda=100:100:1000;                    % wake length in meters
w=2*(R+(lambda/pi));                    % formula for sweep width
plot(lambda,w);grid;xlabel('wake length [meters]');
ylabel('sweep width [meters]');title('sweep width for R=100 meters'); pause

% change detection range R to 500 meters, vary wake length;
R=500;                                  % det range in meters
lambda=100:100:1000;                    % wake length in meters
w=2*(R+(lambda/pi));                     % formula for sweep width
plot(lambda,w);grid;xlabel('wake length [meters]');
ylabel('sweep width [meters]');title('sweep width for R=500 meters'); pause

% change detection range R to 1000 meters, vary wake length;
R=1000;                                 % det range in meters
lambda=100:100:1000;                    % wake length in meters
w=2*(R+(lambda/pi));                    % formula for sweep width
plot(lambda,w);grid;xlabel('wake length [meters]');
ylabel('sweep width [meters]');title('sweep width for R=1000 meters'); pause

% change detection range R to 2000 meters, vary wake length;
R=2000;                                 % det range in meters
lambda=100:100:1000;                    % wake length in meters
w=2*(R+(lambda/pi));                    % formula for sweep width
plot(lambda,w);grid;xlabel('wake length [meters]');
ylabel('sweep width [meters]');title('sweep width for R=2000 meters');pause

% ****************** new section *****************
% now fix wake length and vary det range;
clear
clg

% axis([0 1000 0 3500])
% wake length of 100 meters
lambda=100;                             % wake length in meters
R=100:100:1000;                         % det range in meters, 100 m - 1000m in 100m steps
w=2*(R+(lambda/pi));                    % formula for sweep width
plot(R,w);grid;xlabel('detection range [meters]');
ylabel('sweep width [meters]');
title('sweep width for wake of 100 meters'); pause

% wake length of 500 meters;
lambda=500;                             % wake length in meters
R=100:100:1000;                         % det range in meters, 100 m - 1000m in 100m steps
w=2*(R+(lambda/pi));                    % formula for sweep width
plot(R,w);grid;xlabel('detection range [meters]');
ylabel('sweep width [meters]');
title('sweep width for wake of 500 meters'); pause
```

```
% wake length of 1000 meters;
lambda=1000;                            % wake length in meters
R=100:100:1000;                         % det range in meters, 100 m - 1000m in 100m steps
w=2*(R+(lambda/pi));                    % formula for sweep width
plot(R,w);grid;xlabel('detection range [meters]'); pause
ylabel('sweep width [meters]');
title('sweep width for wake of 1000 meters');

% wake length of 2000 meters;
lambda=2000;                            % wake length in meters
R=100:100:1000;                         % det range in meters, 100 m - 1000m in 100m steps
w=2*(R+(lambda/pi));                    % formula for sweep width
plot(R,w);grid;xlabel('detection range [meters]');
ylabel('sweep width [meters]');
title('sweep width for wake of 2000 meters'); pause
```

LIST OF REFERENCES

1. Benedict, J.R., "Third World Submarine Developments," *Maritime Patrol Aviation*, Vol. 2 No. 2, p.57, March 1992.

2. "Aven Views Shift in Weapons Export Market, Increased Sales," *Interfax*, 30 November 1992 (Trans.: FBIS-SOV-92-234), p. 7, quoted in Zaloga, S., "Harpoonski," *Naval Institute Proceedings*, February 94, page 40.

3. Kraus, G.F. Jr., "World Submarine Proliferation and U.S. Contingencies," *The Submarine Review*, page 61, April 1993.

4. *The Encyclopedia Americana International Edition*, quoted in Benedict, J. "Third World Submarine Developments," The Johns Hopkins University Applied Physics Laboratory, presented to the 8th Annual Naval Submarine League Symposium, 13 June 1990.

5. 1993-94 *Jane's Fighting Ships*, Jane's Information Group Incorporated, Alexandria, VA, 1993, page 11.

6. 10/31/88 and 4/3/89 Navy News & Undersea Technology, quoted in Benedict, J. "Third World Submarine Developments," The Johns Hopkins University Applied Physics Laboratory, presented to the 8th Annual Naval Submarine League Symposium, 13 June 1990.

7. 1/30/90 CNO Intelligence Notes (Unclassified Portion), quoted in Benedict, J. "Third World Submarine Developments," The Johns Hopkins University Applied Physics Laboratory, presented to the 8th Annual Naval Submarine League Symposium, 13 June 1990.

8. 89/90 Jane's Fighting Ships, quoted in Benedict, J. "Third World Submarine Developments," The Johns Hopkins University Applied Physics Laboratory, presented to the 8th Annual Naval Submarine League Symposium, 13 June 1990.

9. Gerken, L., *ASW versus Submarine Technology Battle*, American Scientific Corporation, 1986, page 393.

10. NITA-DA30-006-89 quoted in Benedict, J. "Third World Submarine Developments," The Johns Hopkins University Applied Physics Laboratory, presented to the 8th Annual Naval Submarine League Symposium, 13 June 1990.

11. Fox, H., "Closed Recycling Powers Underwater Diesel Engine," *Sea Technology*, April 1990, page 29.

12. 1993-94 *Jane's Fighting Ships*, Janes's Information Group Incorportated, Alexandria, Virginia, page 642.

13. Breemer, Dr. J.S., "AIP: The Quiet Underwater Revolution," *Maritime Patrol Aviation*, September 1991, page 53.

14. Hill, Rear Admiral J.R., *Anti-Submarine Warfare*, Naval Institute Press, 1985, page 39.

15. Forrest, R.N., "A Program to compute Magnetic Anomaly Detection Probabilities," Technical Report NPS71-88-001 (2d rev), Monterey, March 1990, page 20.

16. Unpublished class notes, Physics 3002, Naval Postgraduate School, Monterey, California.

17. Stefanick, T., *Strategic Antisubmarine Warfare and Naval Strategy*, Institute for Defense & Disarmament Studies, Lexington Books, 1987, page 186.

18. Hargreaves, J.K., *The Upper Atmosphere and Solar Terrestrial Relations*, Van Nostrand Reinhold Company, 1965, quoted in unpublished class handouts, Meteorology (for ASW) 2413, Naval Postgraduate School, Monterey, California.

19. Washburn, A.R., *Search and Detection*, 2d ed., Operations Research Society of America, October 1989, page 4-1.

20. Forrest, R.N., Estimating Search Effectiveness with Limited Information, Technical Report NPS-AW-93-001, September 1993 page 14.

21. Swarner, W.G., et al., Report 2170-5, Subsurface Target Detection Techniques, Technical Report AFAL-TR-67-78, May 1967, page 13.

22. Shifrin, K.S., *Physical Optics of Ocean Water*, American Institute of Physics, translated by Oliver, D., 1983, page 173-175.

23. Hulbert, E.O., "Optics of Distilled and Natural Water," Benchmark Papers in Optics Volume 3 - Light in the Sea, edited by Tyler J.E., Benchmark, 1977, page 135.

24. Slade, S., "Hunting the Sound of Silence," *Naval Forces*, Volume XIV, Number V, 1993, page 25.

25. Herskovitz, D., "Military Computing in the Year 2001 and Beyond," *The Journal of Electronic Defense*, Volume 17, No. 2, February 1994, pages 41-45.

26. Sanders, M.S., and McCormick, E.J., *Human Factors in Engineering and Design*, 7d, McGraw-Hill, 1993, page 100.

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center Cameron Station Alexandria, VA 22304-6145	2
2.	Library, Code 52 Naval Postgraduate School Monterey, CA 93943-5002	2
3.	Director, Submarine Warfare Division Chief of Naval Operations (N87) Pentagon Room 4E453 Navy Department Washington, DC 20350-2000	1
4.	Director, Exeditionary Warfare Division Chief of Naval Operations (N85) Pentagon Room 4A720 Navy Department Washington, DC 20350-2000	1
5.	National Defence Headquarters MGen George R. Pearkes Building Ottawa, Ontario, Canada K1A 0K2 Attention: DPED	1
6.	National Defence Headquarters MGen George R. Pearkes Building Ottawa, Ontario, Canada K1A 0K2 Attention: DMA 3-5	1
7.	LCDR M.D. Kite, Code PH/Ki Department of Physics and Chemistry Naval Postgraduate School Monterey, CA 93943-5002	1
8.	Dr. R.N. Forrest, Code OR/Fo Department of Operations Research Naval Postgraduate School Monterey, CA 93943-5002	1

9.	Dr. J. V. Sanders, Code PH/Sd Department of Physics and Chemistry Naval Postgraduate School Monterey, CA 93943-5002	1
10.	Maj. D.G. Daly 14 Software Engineering Squadron 14 Wing Greenwood Greenwood, Nova Scotia, Canada B0P 1N0	2